

**DEVICE FOR CROSSING OPTICAL BEAMS, IN PARTICULAR IN AN  
INTEGRATED OPTICAL CIRCUIT**

The present invention relates to a device for crossing optical beams,  
5 in particular in an integrated optical circuit.

In optical telecommunication systems, information is typically coded in short optical pulses by suitable optical sources, such as light-emitting diodes (LEDs) or semiconductor lasers, which pulses are transmitted along an optical-fibre network and received by photodetectors. Many different signals  
10 can be transmitted using a single wavelength of light by interweaving the pulses from different sources, a technique known as time-division multiplexing (TDM).

A simple way of increasing the amount of data that can be transmitted by a single optical fibre is to make the incoming electronic bits as short as  
15 possible. Current optical systems have achieved data rates up to 40 gigabits per second.

Recently, transmission capacity has been increased by dense wavelength division multiplexing (DWDM), which requires a very stable emitting laser and, at the receiver, very narrow linewidth filters and optical  
20 switches for separating individual wavelength channels and routing them to the appropriate destinations. Due to the large number of individual components in a DWDM system, integrated optical circuits have been developed. Integrated optical circuits may be either monolithic or hybrid and comprise active and passive components, typically realized on a  
25 semiconductor or dielectric substrate, used for coupling between optoelectronic devices and providing signal processing functions.

Since integrated circuits provide for designing of integrated components and waveguides substantially in a two-dimensional structure, one problem in integrated optical circuits is crossing of different waveguides. This  
30 problem occurs for example in case of optical switching, where a plurality of optical inputs are directed to a plurality of optical outputs, and crossing is

necessary in order for each input to connect to every output.

This problem is addressed for example in US 6,198,860, wherein it is observed that current integration in the wavelength scale requires intersection of waveguides, and not simply pass of the waveguide over the other, since 5 any realizing three-dimensional structures adds considerable manufacturing difficulty. A main problem with waveguide crossing is crosstalk, i.e. undesired redirection of part of a signal conveyed in a waveguide into a crossing waveguide. When two crossing waveguides are conveying respective signals, crosstalk produces an interference between the two signal.

10 US 6,198,860 provides a solution to this problem by providing, at the intersection between two waveguides, a photonic crystal resonator.

Photonic crystals are dielectric structures having a periodic variation (or modulation) of the dielectric constant along one, two or three directions of space (and the crystal is therefore referred to as a 1-D, 2-D or 3-D photonic 15 crystal). A 2-D photonic crystal typically comprises a piece of dielectric material (for example an optically thin slab) wherein a periodic array of regions of different refractive index is realized. These regions may be defined, for example, by cylinders filled of air or other predetermined substances or materials.

20 Photonic crystals have band gaps that restrict the propagation of light in certain frequency ranges. Their discovery in recent years has caused a rethinking of conventional methods for manipulating light, and has led to proposals for many novel optical devices. In particular, it has been shown that a linear defect in a photonic crystal (i.e. a break in the periodicity of the crystal 25 along one line) allows light with wavelength within the bandgap to be guided, by relying on the band gap restriction instead of index confinement to prevent light from escaping. Similarly, a defect at a single location (a point defect) creates a resonant cavity, which traps light in a small region.

The waveguide crossing design proposed in US 6,198,860 makes 30 uses of both of these phenomena, since light is guided to the crossing region through linear defects, while the crossing region contains a single defect

defining a resonant cavity. Fig. 1 shows one possible embodiments as depicted in US 6,198,860. A photonic crystal 10 has a first and a second waveguide 11, 12 perpendicular to each other, defined by respective linear defects, and a resonant crossing region 13, formed by a single defect. The 5 single defect is defined by a dielectric rod of larger radius than the other rods of the crystal.

As far as the guided mode is concerned, the situation is described by simple one-dimensional resonant tunneling, wherein the crossing waveguide is effectively invisible. In particular, when a guided mode is incident upon the 10 crossing from one of the waveguides, it can only couple to the resonant state that is symmetric with respect to the axis of that waveguide. The other resonant state, which is anti-symmetric, is orthogonal to that guided mode by symmetry. Correspondingly, the symmetric resonant state can only decay into the input and output waveguides, since this state is orthogonal to the modes 15 in the crossing waveguide.

This structure allows optical modes to propagate with 100% transmission (throughput) from an input waveguide to the output waveguide on the opposite side of a crossing, with no reflection and with 0% transmission (crosstalk) to the crossing waveguide.

20 The Applicant, tackling the problem of avoiding crosstalk in intersecting optical waveguides, has searched for alternative solutions.

In particular, the Applicant has considered possible different X-crossing structures using photonic crystals.

Besides development of photonic crystals devices having defects, 25 behaviour of light in photonic crystals having regular periodicity (herein below also referred to as "regular photonic crystals"), has been investigated. For the purposes of the present invention, with "photonic crystals having regular periodicity" it is intended a photonic crystal wherein the characteristics of its periodic array do not vary at least in a region thereof of intended light propagation.

30 The article of *P. Etchegoin and R. T. Phillips, "Photon focusing,*

internal diffraction, and surface states in periodic dielectric structures", *Physical Review B*, Volume 53, Number 19, 15 May 1996-1, takes advantage of some analogies between electrons in semiconductors and electromagnetic waves in periodic dielectric structures for providing a method for calculation 5 the band structure of a 2-D periodic dielectric structure. Moreover, this article deals with the phenomenon of photon focusing emitted by a source point in these structure, in analogy with the phenomenon of acoustic phonon focusing, showing what shape shall have the  $k_x$ - $k_y$  diagram of the wave vector  $\mathbf{k}$  to have focusing of light along predetermined directions.

10 The Applicant observes that, besides having been studied only at theoretical level, applications of photon focusing would be of limited use in integrated optics.

15 The article of *Marko Lončar, Jelena Vučković and Axel Scherer, "Three-dimensional analysis of dispersion properties of planar photonic crystals", Proceedings of PECS III conference (June 2001), St. Andrew's, Scotland*. shows that a planar (i.e. 2-D) photonic crystal may have, under certain conditions, a self-collimation effect in the second energy band (i.e. the energy band over the fundamental band). As disclosed in the article, these conditions determine a negative group velocity.

20 The Applicant observes that, for the time being, no practical applications have been shown of a beam of light (although collimated) having a negative group velocity.

25 The Applicant has further investigated the light propagation properties of regular photonic crystals and considered the possibility of using such structures for X-crossing purposes.

The Applicant has found that, by opportunely choosing the geometrical and physical characteristics of a photonic crystal and the operative wavelength, it is possible to use such photonic crystal at said wavelength as a X-crossing device having no crosstalk. This particular device has no 30 predefinite waveguide since the beams propagating into the device self-collimate, due to an effect of "photon guiding" characteristic of a photonic

crystal designed according to the teaching of the present invention. Collimated propagation is allowed along the crystal axes, and the device is therefore suitable for crossing of two beams if the periodic array of the photonic crystal has a square geometry, and two or three beams if the 5 periodic array has a triangular geometry.

The present invention therefore relates to device for crossing optical beams, comprising at least first input optical waveguide directed along a first axis and a second optical waveguide directed along a second axis inclined with respect to the first axis, and further comprising an optical crossing region 10 at the intersection of said first and second axis, wherein it comprises a photonic crystal having a regular periodicity in said optical crossing region.

Preferably, the device further comprises a first and a second output optical waveguide opposite said first and second input optical waveguide with respect to said crossing region and directed along said first and second axis, 15 respectively.

Preferably, said first and second axis have the same direction of a first and a second crystal axis, respectively, and said first and second axis are perpendicular to each other.

Said photonic crystal may extend in a square or rectangular portion of an 20 optical integrated structure and said first and second input optical waveguides may be coupled to respective edges of said portion.

The photonic crystal may have a periodic array of holes arranged according to a square geometry.

The said first and second directions may also define an angle of  $\pi/3$ , 25 the photonic crystal may extend in a substantially hexagonal portion of an optical integrated structure and said first and second input optical waveguides may be coupled to respective edges of said portion.

The photonic crystal may also have a periodic array of holes arranged according to a triangular geometry.

30 The device may further comprise a third input optical waveguide directed along a third axis that intersects said first and second axis in said crossing

region.

The device may also comprise a third output optical waveguide opposite said third input optical waveguide with respect to said crossing region and directed along said third axis.

5 At least one of said first and second input optical waveguide may be an integrated waveguide, or alternatively an optical fibre.

Preferably, said optical beams have predetermined wavelengths, the photonic crystal is made of a bulk material having a first refractive index and includes a periodic array of regions having a second refractive index different 10 from the first and having predetermined dimensions, and the difference between said first and second refractive indices, the dimensions of said regions and the period of said array are so related to each other and to said wavelengths that, starting from a isotropic distribution of the wave vectors of said electromagnetic radiation within a first angular range that is twice the 15 angular extension of the first Irreducible Brillouin zone of said photonic crystal, the group velocity vectors corresponding to said wave vectors are rearranged during propagation in said photonic crystal so that at least 50% of the group velocity vectors are directed within a second angular range that is about one-third of said first angular range and the width at half-maximum of the 20 distribution of the modules of said group velocity vectors is lower than about two-third of said second angular range.

The waveguide may be realized on the substrate layer and may be a ridge waveguide, a rib waveguide or a photonic crystal waveguide having a linear defect region.

25 Further details may be obtained from the following description, which refers to the accompanying drawings listed below:

**Figure 1** is an illustrative representation of a 2-D photonic crystal having a regular periodicity;

30 **Figure 2a** schematically shows a device for propagating a light beam through a photonic crystal according to the present invention, and **2b** show a possible arrangement (triangular in this case) of the holes in a photonic

crystal;

**Figure 3** is an illustrative representation of an energy band diagram for a photonic crystal having a triangular array of holes;

5 **Figure 4a** and **4b** show diagrams of wave-vectors  $\underline{k}$  and group velocities  $\underline{v}_g$  suitable for observing waveguiding in a photonic crystal;

**Figure 5** is an illustrative representation of the distribution of group velocities  $\underline{v}_g$  in the direction of a crystal axis;

**Figure 6** is an illustrative perspective view of a device for waveguiding electromagnetic radiation according to the present invention;

10 **Figure 7a** and **7b** show possible X-crossing devices made in accordance to the present invention;

**Fig. 8** shows a device for producing a sharp bend of a light beam, according to the present invention; and

15 **Figures 9a-9d, 10a-10d, 11, 12 and 13** relate to results of numeric simulations.

With reference to **Figs. 1, 2a** and **2b**, it is indicated with 1 a photonic crystal comprising a bulk body 2 made of a dielectric material, wherein a periodic array of holes 2 has been realized. Although a bi-dimensional (2-D) photonic crystal is described, the teaching of the present invention may be 20 extended to three-dimensional (3-D) photonic crystals as well, i.e. crystals having a 3-D distribution of regions of different refractive index than the bulk, such as spheres.

25 The bulk dielectric material has a refractive index  $n$  preferably greater than 1.5. Possible materials are  $\text{SiO}_2$ ,  $\text{SiO}_x\text{N}_y$ ,  $\text{GaAs}$ ,  $\text{Si}$ ; this list is only illustrative and not exhaustive.

30 Preferably, holes 2 contain air, are cylindrical and parallel to each other and have a same radius  $\rho$ . As shown in **Fig. 2b**, holes 2 may be arranged to form a triangular array having a period  $a$ . Although an arrangement according to an equilateral triangle is illustrated, an arrangement according to an isosceles triangle may be used, as well. Alternatively, holes 2 may be arranged according to a square or a rectangular array. In general, the

periodicity of the array is the periodicity of the "cells", each "cell" including three holes for triangular arrays and four holes in square or rectangular arrays.

It can be shown that the preferred transmission directions are those corresponding with the crystal axes. In case of triangular geometry, the crystal axes are those connecting the vertices of the triangles, while in case of square or rectangular geometries the crystal axes correspond to the diagonals of the square or triangle, i.e. the axes connecting opposite vertex. In case of triangular array geometry the three crystal axes are angularly spaced at  $60^\circ$  ( $\pi/3$ ), while in case of square array geometry the two crystal axes are angularly spaced at  $90^\circ$  ( $\pi/2$ ).

Although the description that follows is referred to a photonic crystal having holes 2 filled with air and of circular cross-section, the teaching of the present inventions extends to photonic crystals wherein the holes contain a predetermined substance different from air or are substituted by rods of a predetermined dielectric material (of different refractive index than the bulk dielectric material), and wherein the holes have cross-sections other than circular, for example square.

In accordance with the above, photonic crystal 1 has a structure that does not vary along an axis z parallel to the axes of holes 2, and that varies periodically in a plane x-y perpendicular to axis z.

Method of manufacturing photonic crystal 1 will not be described in that methods known in the art can be used. Methods for manufacturing photonic crystals and devices comprising photonic crystals are described, for example, in US 5,526,449, US 6,064,511 and in the article of *M. Lončar, T. Doll, J. Vučković and A. Scherer, "Design and Fabrication of Silicon Photonic Crystal Optical Waveguides", Journal of Lightwave Technology, Vol. 18, No. 10, October 2000.*

The parameters that determine the guiding characteristics of the photonic crystal 1 are the relative spacing  $R$ , defined as the ratio between the period  $a$  of the array of holes 2 and the radius  $\rho$  of holes 2, the refractive

index  $n$  of the dielectric material (or, in general, the difference of refractive index between the bulk dielectric material and the substance or material filling the holes), and a further parameter, known as "normalized frequency" and indicated with  $\omega_n$ , proportional to the ratio between the period  $a$  and the 5 wavelength  $\lambda$  of the electromagnetic radiation to be guided.

The condition of "photon guiding", or "waveguiding", is achieved if the photonic crystal 1 is so designed, and the electromagnetic radiation propagating therein has such a wavelength, that a substantial fraction of the energy of the electromagnetic radiation is made to flow in a direction 10 coinciding with one of the crystal axes. The "photon guiding" condition will herein below defined by reference to a well-known vector parameter of the electromagnetic radiation, the "group velocity", whose direction corresponds to that of energy propagation. In practice, starting from an isotropic distribution of the group velocities, "photon guiding" occurs when said distribution is so 15 modified that:

- a predetermined percentage of the group velocities is oriented within a predetermined sub-range of the original angular range;
- the angular distribution of the module of the group velocities shows a peak along the considered propagation axis, and has a width at 20 half-maximum lower than a predetermined value.

In other words, the photon crystal shall be so designed that the group velocities converge towards the desired propagation direction and that most of the energy of the propagating beam is carried by the group velocities so directed.

25 For the purposes of the present invention, a condition of "photon guiding" of an electromagnetic radiation in a predetermined direction within a photonic crystal is a condition wherein, starting from a isotropic distribution of the wave vectors of said electromagnetic radiation within a first angular range that is twice the angular extension of the first (irreducible) Brillouin zone of the 30 photonic crystal, the group velocity vectors corresponding to said wave vectors are rearranged as concerns direction and module so that at least

50% of the group velocity vectors become directed within a second angular range that is about one-third of the first angular range and the width at half-maximum of the distribution of the modules of the group velocity vectors is lower than about two-thirds of the second angular range.

5 In a preferred condition, the width at half-maximum of the distribution of the modules of said vectors is lower than about one-half of the second angular range.

In the description that follows, the angular distribution of the group velocity will be indicated with as  $r(\theta)$ .

10 In the previous definition of "photon guiding", as in the following of the present description, the width at half-maximum of a distribution  $r(\theta)$  will be considered as equivalent to the variance of the distribution, wherein the variance  $\sigma$  is so defined:

$$15 \quad \sigma = \sqrt{\frac{\sum_i (\theta_i - \mu)^2 \cdot r(\theta_i)}{\sum_i r(\theta_i)}}$$

where  $\theta_i$  indicates the angle with respect to the considered direction, and  $\mu$  is the average of said distribution about said direction and is equal to 0 for a triangular array and to  $\pi/4$  for a square array.

20 Preferred conditions for photon guiding may be expressed in terms of variance  $\sigma$ . In case of a triangular geometry, a preferred condition of "photon guiding" along a crystal axis occurs when, starting from a isotropic distribution of the wave vectors within an angular range of  $60^\circ$  ( $\pi/3$ ) about said axis (which is twice the angular extension of the first irreducible Brillouin zone), the group velocity vectors corresponding to said wave vectors are rearranged, as  
25 concerns module and direction, so that at least 50% of the group velocity vectors become directed within an angular range of  $20^\circ$  ( $\pi/9$ ) about said axis (i.e. within an angular range that is one-third of the original one) and the variance  $\sigma$  of the module distribution about said axis is lower than about 0.15

rad (i.e.  $\sigma^2 < \sim 0.022 \text{ rad}^2$ ). A better guiding effect may be observed for  $\sigma$  lower than about 0.13 rad (i.e.  $\sigma^2 < \sim 0.017 \text{ rad}^2$ ) and a still better guiding effect for  $\sigma$  lower than about 0.11 rad (i.e.  $\sigma^2 < \sim 0.012 \text{ rad}^2$ ). Choosing a more or a less restrictive condition (in terms of  $\sigma$ ) may depend on the particular requirements 5 and conditions, for example on the distance to be covered through the photonic crystal.

In case of a square geometry, a preferred condition of "photon guiding" along a crystal axis occurs when, starting from a isotropic distribution of the wave vectors within an angular range of  $90^\circ$  ( $\pi/2$ ) about said axis (which 10 is twice the angular extension of the first irreducible Brillouin zone), the group velocity vectors corresponding to said wave vectors are rearranged, as concern module and direction, so that at least 50% of the group velocity vectors become directed within an angular range of  $30^\circ$  ( $\pi/6$ ) about said axis (i.e. within an angular range that is one-third of the original one) and the 15 variance  $\sigma$  of the module distribution about said axis is lower than about 0.22 rad (i.e.  $\sigma^2 < \sim 0.049 \text{ rad}^2$ ). A better guiding effect may be observed for  $\sigma$  lower than about 0.17 rad (i.e.  $\sigma^2 < \sim 0.029 \text{ rad}^2$ ) and a still better guiding effect for  $\sigma$  lower than about 0.12 rad (i.e.  $\sigma^2 < \sim 0.014 \text{ rad}^2$ ).

Propagation under "photon guiding" further requires that the 20 electromagnetic radiation has a wavelength in the fundamental photonic band. It can be shown that the above condition of "photonic guiding" is achieved where the surface of the fundamental energy band (in the  $\omega, k_x, k_y$  space) shows an inflection.

Therefore, differently from waveguiding into conventional photonic 25 crystals, wherein light at a wavelength within the photonic band-gap is conveyed through a localized and unchangeable waveguide typically defined by a line of defects in the photonic crystal, waveguiding into a photonic crystal according to the present invention can occur at a wavelength within the fundamental photonic band and in any region of the photonic crystal of regular 30 periodicity. In practice, a "virtual waveguide" is created when a beam of light is

made to propagate into a photonic crystal according to the present invention, since the particular propagation conditions "observed" by the beam of light force it to collimate.

It can therefore be appreciated that the photonic crystal of the present  
5 invention does not require any physical waveguide structure such as the linear  
defect regions of conventional photonic crystals. Dimension and position of a  
collimated guided beam in the photonic crystal of the present invention are  
determined by, and correspond to, dimension and position of the input light  
beam, while the possible propagation directions are those correspond to the  
10 crystal axes.

Therefore, if photonic crystal 1 is optically coupled to an optical  
source suitable to emit electromagnetic radiation at a predetermined  
wavelength, and if this wavelength is so related to the physical characteristics  
15 of the photonic crystal 1 to satisfy the conditions for photon guiding, a device  
suitable to guide a beam of light at this wavelength can be realized. **Fig. 2a**  
shows schematically an optical source 4, for example a known type of laser,  
optically coupled to photonic crystal 1 by means of a first optical waveguide 5  
of a known type, for example an optical fibre or an integrated optical  
waveguide. A second optical waveguide 7 of a known type is coupled to the  
20 photonic crystal 1 opposite the first waveguide 5. Also schematically  
represented is a beam of light 6 generated by the optical source 4 and fed to  
the photonic crystal 1 via the first waveguide 5, which is then propagated  
substantially collimated into the photonic crystal 1 and exits the photonic  
crystal 1 via the second waveguide 7.

25 A further important characteristic of the photonic crystal of the present  
invention is that a plurality of light beams, possibly of different dimensions and  
directions, can be transmitted simultaneously in the crystal. In particular, it is  
possible to transmit two or more light beam in the crystal that cross each other  
so as to define a "X-crossing" structure. The Applicant has verified that in  
30 such a crossing there is no interaction (i.e., no cross-talk) between the  
electromagnetic fields of the two beams. Possible X-crossing will be described

in the following.

A same photonic crystal according to the present inventions may be therefore applied in different ways, for example for guiding a plurality of parallel light beams evenly or differently spaced from each other and having

5 the same or different dimensions, or for guiding a plurality of light beam propagating along different directions (coinciding with crystal axes) and having the same or different directions, which may cross each other in a same or in different regions of the crystal (for example: a beam propagating in a first direction may cross, one after the other, two further beams propagating in a

10 second direction; three beams propagating in three different directions may cross in a same region).

When a plurality of optical beams are propagated, these beams may have a same wavelength or different wavelengths, provided that these wavelengths are suitable for photon guiding in the considered photonic crystal

15 according to the teaching of the present invention.

The Applicant has verified that preferred ranges of the relevant parameters  $n$ ,  $R$  and  $\omega_h$  for achieving the said condition of "photon guiding" are, for triangular and square array geometries, the following:

- for triangular array geometry:

20 • relative spacing  $R$ : between 0.15 and 0.5, more preferably between about 0.20 and 0.45, still more preferably between about 0.25 and 0.4;

• refractive index  $n$ : between 1.5 and 4.5, more preferably between 2.5 and 3.5;

25 • normalized frequency  $\omega_h$ : between about 0.17 and 0.42, more preferably between about 0.25 and 0.40.

- for square array geometry:

30 • relative spacing  $R$ : between 0.15 and 0.5, more preferably between about 0.20 and 0.45, still more preferably between about 0.25 and 0.4;

• refractive index  $n$ : between 1.5 and 4.5, more preferably

between 2.5 and 3.5;

- normalized frequency  $\omega_h$ : between about 0.17 and 0.42, more preferably between about 0.25 and 0.40

As described in the following, there is a relation among these three parameters, so that when two of the three parameters are chosen, the third is fixed.

To find the optimum value ranges of the relevant parameters  $R$ ,  $n$  and  $\omega_h$ , the following method can be followed.

The method comprises analysing the group velocity distribution resulting from the possible combinations of values of the parameters  $R$ ,  $n$  and  $\omega_h$  within predetermined ranges and determining the set of combinations that provide a group velocity distribution suitable to have photon guiding according to the above teaching.

To this aim, a theoretical model the crystal, such as the model proposed in the above-cited article of *P. Etchegoin and R. T. Phillips*, may be advantageously applied. This model can be initially used for determining the band diagram of the crystal when a couple of values of  $n$  and  $R$  has been established and can be then used to determine the distribution of the group velocities when predetermined values of  $R$ ,  $n$  and  $\omega_h$  are considered.

If a 2-D dielectric structure as in **Fig. 1** is considered, in particular having an extension along the  $x$  and  $y$  axes much greater than along the  $z$ -axis, an electromagnetic band structure as in the illustrative representation of **Fig. 3** is obtained, where  $\Gamma$ ,  $M$  and  $K$  are the well-known parameters identifying the first Irreducible Brillouin zone, and the continuous and dashed lines correspond to the TE and TM modes, respectively. As concerns the TE modes, a fundamental photonic band (or first band), here indicated with BAND I, and a photonic band-gap PBG, separating the fundamental band BAND I from a second photonic band BAND II, may be identified.

As known from theory of electromagnetic propagation in anisotropic media, energy does not flow in the same direction of  $\underline{k}$ . When energy is

represented by dispersion relation  $\omega(\underline{k})$ , it is easily demonstrated that energy flows in the direction of the group velocity  $\underline{v}_g = \nabla_{\underline{k}} \cdot \omega(\underline{k})$ . In fact, it can be shown formally that  $\underline{v}_g$ , obtained as a gradient of  $\omega(\underline{k})$ , coincides with the direction of the Poynting vector  $S \propto \underline{E} \times \underline{H}$  for electromagnetic waves. Therefore, the 5 electromagnetic band structure provides a relation  $\omega = \omega(\underline{k})$ , from which the group velocity  $\underline{v}_g$  can be obtained.

For a predetermined energy it is possible to define two surfaces: the constant energy surface, represented in the  $k_x$ - $k_y$  plane, obtained directly by the intersection of the 3-D band surface (in the space  $\omega$ ,  $k_x$ ,  $k_y$ ) with a plane 10 with constant abscissa equal to given energy value; and the wave surface, formed by the locus of all possible group velocities and represented in the  $v_{gx}$ - $v_{gy}$  plane. The wave surface represents the wave front that would emerge from a point source. It can be shown that, for each point of the constant 15 energy surface, the corresponding group velocity is directed perpendicular to said surface. Said article *P. Etchegoin and R. T. Phillips* illustrates possible shapes for these surfaces for photon phocusing.

In order to have a collimated guiding of light within the crystal, these surfaces shall have particular shapes, in particular the constant energy surface (in the  $k_x$ - $k_y$  plane) shall have straight portions with the broadest 20 possible extension, and the group velocities shall be directed outwards with respect to the centre of the diagram. The wider and the flatter are said portions, the larger will be the range of group velocities having the same direction (i.e. the more collimated will be the guided light). In a triangular array geometry, to have a substantially collimated transmission, the constant energy 25 surface shall have a substantially hexagonal shape, with straight portions defining the edges of the hexagon. Differently, in a square array geometry, the constant energy surface shall have a substantially square shape, and the group velocities will be highly concentrated in the directions perpendicular to the four edges, i.e. in four different directions equally angularly spaced (of 30  $\pi/2$ ).

**Fig. 4a** shows, illustratively, a constant energy surface ( $k_x$ - $k_y$  plane) of a type suitable for having collimated guiding in case of a triangular array geometry and for the TE mode of a monomode electromagnetic radiation, and **Fig. 4b** shows the corresponding wave surface ( $v_{gx}$ - $v_{gy}$  plane).

5 In the simulation, a isotropic distribution of the group velocities, and in particular an isotropic distribution of the wave vectors about a predetermined crystal axis in an angular range of  $\pi/3$  for a triangular array, and of  $\pi/2$  for a square array, has to be considered as a starting condition, and the parameters  $R$ ,  $n$  and  $\omega_h$  may be varied for example as follows.

10 The parameter  $R$  may be varied in a range that is chosen by taking into account the current technological difficulties in realizing large aspect ratio holes arrays in photonic crystals. A suitable range is for example between 0.15 and 0.45.

15 The parameter  $n$  may be varied in a range of values including those of the currently most suitable dielectric materials for the manufacturing of photonic crystals, such as  $\text{SiO}_2$ ,  $\text{SiO}_x\text{N}_y$  and  $\text{GaAs}$ : for example the values 1.5, 2, 2.5, 3.25 and 3.5 may be considered.

20 The third parameter  $\omega_h$  may be varied of a predetermined amount (for example  $1 \cdot 10^{-4}$ ) in a predetermined range, for example starting from the maximum value  $\omega_{h,max}$  of the first band, until a predetermined condition is satisfied, as explained below.

25 The simulation model previously mentioned may be advantageously applied in this stage to each couple of values of  $R$  and  $n$  within the specified ranges, determining each time the value of  $\omega_h$  that optimizes the distribution of the group velocity  $r(\theta)$ .

30 In particular, for each couple of values of  $R$  and  $n$ , the parameter  $\omega_h$  is varied of the predetermined amount until the group velocity distribution  $r(\theta)$  is optimised in terms of average  $\mu$ , variance  $\sigma$ , height  $\Delta h$ , kurtosis  $K$  and percentage of representative points that are within a predetermined angular range  $\Delta\theta$  about the considered direction. This angular range, as previously

stated, is chosen equal to  $\pi/9$  for a triangular array geometry and  $\pi/6$  for a square array geometry. In particular, the optimum value of  $\omega_n$  is the one that minimizes  $\sigma$  and  $K$  and maximizes  $\Delta h$  and the percentage of points within the angular range  $\Delta\theta$ . **Fig. 5** is an illustrative representation of a group velocity distribution, with an indication of the said parameters, which are defined as follows (definition of  $\sigma$  is reported again for sake of clarity):

$$\Delta h = \frac{\max(r(\theta)_{|\theta| < \Delta\theta}) - \min(r(\theta)_{|\theta| < \Delta\theta})}{\min(r(\theta)_{|\theta| < \Delta\theta})};$$

$$\sigma = \sqrt{\frac{\sum_i (\theta_i - \mu)^2 \cdot r(\theta_i)}{\sum_i r(\theta_i)}}$$

10 where  $\mu=0$  for a triangular array and  $\mu=\pi/4$  for a square array ; and

$$K = \frac{\sum_i (\theta_i - \mu)^4 \cdot r(\theta_i)}{\sum_i r(\theta_i)}.$$

When  $\omega_n$  is equal to its optimum value, the curve of the group velocity distribution is relatively sharp and has the maximum height  $\Delta h$ . If  $\omega_n$  is varied in one direction or the other with respect to its optimum value, the distribution 15 undergoes an abrupt decrease of  $\Delta h$ , and an increase of the kurtosis  $K$  and of the variance  $\sigma$ . In particular, variations of the parameter  $\omega_n$  with respect to said optimum condition determine either a broadening of the distribution or the appearance of a ring in the curve, and it can be demonstrated that both conditions are undesirable.

20 When the optimum value of  $\omega_n$  is found for a predetermined couple of values of  $n$  and  $R$ , it is checked if the values of the variance  $\sigma$  and of the percentage of points within the specifies angular range for the considered tern of values of  $n$ ,  $R$  and  $\omega_n$  satisfies the above-mentioned conditions for photon

guiding.

All the terms of value of  $R$ ,  $n$  and  $\omega_h$  so detected identify a crystal structure, a bulk material and a wavelength suitable to have photon guiding.

**Fig. 6** illustrates an integrated optical device 200 comprising a substrate 207 and a plurality of layers superimposed on a z direction, in particular a decoupling layer 202, a first cladding layer 203, a core layer 204 and a second cladding layer 205. The refraction index of the core layer 204 is higher than that of the first and second cladding layers 203, 205. The refractive index of the decoupling layer 202 is lower than that of the first 10 cladding layer 203.

Moreover, device 200 has a periodic array of holes 2 that cross layers 205, 204, 203 and 202 along the z direction down to the substrate 207, thus defining a photonic crystal 201. Photonic crystal 201 is designed according to the present invention. Besides providing a photon guiding effect in a x-y 15 plane, device 200 also confines light in the z direction inside the core layer 204, due to the difference of refraction index of the core layer 204 with respect to the first and second cladding layers 203, 205.

Photonic crystal 201 may be interfaced with different types of conventional waveguides for the input and the output of light, such as ridge 20 waveguides (with shallow edge or deep edge, the latter being also known as "mesa"), rib waveguides, photonic crystal waveguides (with linear defect regions). The input and output of light may be also performed by means optical fibers, in particular by facing the core of the fiber to the core layer 204. In the illustrative example of **Fig. 6**, device 200 includes a mesa waveguide 25 210 integrally connected to the photonic crystal 201. Mesa waveguide 210 extends along a direction corresponding to one of the crystal axes of the photonic crystal 201 and has a succession of layers corresponding to those of photonic crystal 201 so that, in the manufacturing process, it may be grown together with photonic crystal 201.

As an example, a device suitable to operate at 1550 nm has a substrate 207 made of GaAs having a refractive index (measured at 25°) of

3.374, a core layer 204 made of  $Al_{0.37}Ga_{0.63}As$  having a refractive index (measured at 25°) of 3.25, first and second cladding layers 203, 205 having a refractive index of 0.01 lower than that of the core layer 204 (by using a different percentage of Al), and a decoupling layer 202 that, in turn, has a refractive index of 0.01 lower than that of the cladding layers 203, 205 (by using a different percentage of Al). The characteristic parameters of the considered photonic crystal are  $n=3.25$ ,  $R=0.42$  and  $\omega_n=0.26$ . The radius  $\rho$  of holes 2 is 93 nm and the period  $a$  of the array is 311 nm. Holes 2 are arranged according to a triangular array and are filled of air.

Such a device provides a  $k_x$ - $k_y$  and  $v_{gx}$ - $v_{gy}$  diagrams as those represented in **Figs. 4a and 4b**.

Device 200 is only an illustrative example and, in general, a photonic crystal according to the present invention may be used in any type of planar waveguiding structure able to confine light in the z direction.

**Fig. 7a** and **7b** are illustrative representation of two different X-crossing devices 300, 400 that make use of a photonic crystal according to the present invention, with a triangular and square arrangement of holes 2, respectively. In particular, device 300 comprises a hexagonal photonic crystal structure 301 having a periodic array of holes 2 with equilateral triangular array geometry, and three couples of opposite waveguides 302, 303, 304 directed along the crystal axes, here indicated with  $x_1$ ,  $x_2$  and  $x_3$ . Each couple of waveguides 302, 303, 304 includes an input waveguide 302', 303', 304' and an output waveguide 302'', 303'', 304''. Waveguides 302, 303 and 304 may be, for example, conventional waveguides in integrated optics, or be defined by linear defects regions of a photonic crystal. Alternatively, in place of one or more of waveguides 302, 303 and 304, there may be a corresponding optical fiber (not shown) facing the edge of the photonic crystal.

In use, three different beams of light A, B, C, carrying respective signals and having a same wavelength or close different wavelengths suitable for photon guiding, are fed to the photonic crystal 301 via the input

waveguides 302', 303', 304' and propagate collimated into the photonic crystal 301. In the centre of the photonic crystal 301, the three beams A, B, C cross each other. It has been verified that this crossing occurs without mutual interaction among the beams, i.e. without cross-talk. After crossing, the 5 beams continue their propagation to reach the respective output waveguides 302'', 303'', 304'' so that they can exit the device.

A device with an isosceles triangle array geometry may alternatively be used, and the directions of the input and output waveguides shall be varied accordingly, in order to coincide with the directions of the crystal axes.

10 It can be appreciated that a couple of waveguide may be omitted from device 300, so as to have a device that is simpler but is suitable for crossing only two beams of light.

Device 400 comprises a square photonic crystal structure 401 having a periodic array of holes 2 arranged according to a square geometry, and two 15 couples of opposite waveguides 402, 403 directed along the crystal axes, here indicated with x and y. Each couple of waveguides 402, 403 includes an input waveguide 402', 403' and an output waveguide 402'', 403''. Waveguides 402, 403 may be, for example, conventional waveguides in integrated optics, or be defined by linear defects regions of a photonic crystal. Alternatively, in 20 place of one or both of waveguides 402, 403, there may be a corresponding optical fiber (not shown) facing the edge of the photonic crystal.

In use, two different signals A and B are fed to the photonic crystal 401 via the input waveguides 402', 403', propagate collimated into the photonic crystal 401, cross each other in the centre thereof without mutual 25 interaction, and continue their propagation by entering the output waveguides 302'', 303'', 304''. Therefore, two different beam of light can cross each other without crosstalk along two directions at 90° to each other.

A device comprising a rectangular structure and/or a rectangular geometry of the array of holes 2 may be used as well.

30 Photonic crystal structure 301 may be a simple photonic crystal slab or a multi-layer device as in Fig. 6. Moreover, the waveguides may be of

different types, as previously mentioned with reference to the device of Fig. 6.

It can be appreciated that, in its simplest configuration, the X-crossing device only requires a first and a second input optical waveguides directed along two axis inclined to each other and a photonic crystal in the optical crossing region at the intersection of said axes. After crossing, the beams may be propagated in any way, for example by conveying them again in optical waveguides as previously described, or by subjecting one or both to bending as herein below described, or by processing one or both by means of an integrated optical device before further waveguiding.

10 The different beams of light may have a same wavelength or different wavelengths allowing photon guiding.

15 **Fig 8** shows a device 500 for sharply bending a beam of light. Device 500 comprises a slab 501 of dielectric material of refractive index  $n_1$  that defines, in a portion thereof, a photonic crystal 502 according to the present invention. In the particular example here illustrated, the photonic crystal 502 has a periodic array of holes 2 with square geometry and has therefore two perpendicular crystal axes x, y. One portion of slab 501 has been removed by known techniques so as to define an air gap 505, i.e. a region of space with refractive index  $n=1$ . The interface between the photonic crystal 502 and the 20 air gap 505 defines a reflecting surface 506. Surface 506 is so oriented that the normal to surface 506 bisects the two crystal axes x, y.

25 Device 500 further comprises a first and a second waveguide 507, 508 of a known type, made of a material having a second refractive index  $n_2$  different from  $n_1$ . First and second waveguides 507, 508 are directed along the crystal axes x and y, respectively, and end at the borders of the photonic crystal 502.

30 In use, one of the two waveguides, for example the first waveguide 507, conveys a beam of light A into the photonic crystal 502. The photonic crystal 502, if the wavelength of the beam A is so related to the refractive index  $n_1$  and to the period and radius of the holes 2 as previously described (i.e. so as to satisfy the "photon guiding" condition), guides the beam A along

axis y to the reflecting surface 506 and, after reflection, along axis x to the second waveguide 508, where it is newly conveyed in a conventional way.

It can be appreciated that the reflecting surface may be defined in different ways, for example by providing an interface different from air.

5        The array of holes may also have a different geometry, such as rectangular or triangular. In case of triangular array geometry, reflection may occur at different angles, provided the normal to the reflecting surface bisects the two considered propagation axes; for example, when holes are arranged according to an equilateral triangle, reflection may occur at  $60^\circ$  ( $\pi/3$ ) or  $120^\circ$  ( $2\pi/3$ ). Input and output waveguides shall be oriented accordingly.

10

### Example 1

15        In a first set of simulations, it is shown how the characteristics parameters  $R$ ,  $n$  and  $\omega_n$  can be selected for achieving photon guiding. The simulation model previously described has been used for determining the group velocity distributions for different combination of values of said parameters. A photonic crystal having a (equilateral) triangular array of air holes and an initial isotropic distribution of the group velocities has been

20        considered. The analysis is limited to the first dispersion band of the mode TE and it is performed by expressing the group velocity in polar coordinates.

A isotropic distribution of group velocities about a predetermined crystal axis in an angular range of  $\pi/3$  for a triangular array, and of  $\pi/2$  for a square array, has been considered.

25        The parameter  $R$  has been varied between 0.15 and 0.45 by steps of 0.3; as concern the parameter  $n$ , the values 1.5, 2, 2.5, 3.25 and 3.5 have been considered; the parameter  $\omega_n$  has been varied of steps of  $1 \cdot 10^{-4}$ .

30        **Figs. 9a-9d** show the group velocity distributions for  $R=0.21$  and  $n$  varying in the set of values 2, 2.5, 3.25 and 3.5. The abscissa axis represents the angles (in rad) and the ordinate axis indicates the normalized value of the

group velocity. For each graph, the optimum value of  $\omega_n$  has been found by varying this parameter by steps of  $1 \cdot 10^{-4}$ . Electromagnetic radiation of polarization TE and wavelength in the fundamental photonic band has been considered.

5 Table I reports, for the different curves of Figs. 9a-9d, the value of  $n$  and the optimum value of  $\omega_n$ , together with the values of the square of variance ( $\sigma^2$ ), of the kurtosis ( $K$ ), of the height of the group velocity angular distribution ( $\Delta h$ ), and of the percentage of points ( $N$ ) originally in a range of  $\pi/3$  about the considered propagation direction that have been concentrated within an 10 angular range of  $\pi/9$ .

TABLE I ( $R=0.21$ )

	$n$	$\omega_n$	$\sigma^2 [\text{rad}^2]$	$K [\text{rad}^4]$	$\Delta h$	$N [\%]$
<b>Fig. 9a</b>	2	0.2954	$2.5101 \cdot 10^{-2}$	$3.41 \cdot 10^{-3}$	0.35	38
<b>Fig. 9b</b>	2.5	0.2377	$2.0244 \cdot 10^{-2}$	$4.08 \cdot 10^{-3}$	1.77	53
<b>Fig. 9c</b>	3.25	0.1839	$1.7702 \cdot 10^{-2}$	$4.46 \cdot 10^{-3}$	2.5	62
<b>Fig. 9d</b>	3.5	0.171	$1.7793 \cdot 10^{-2}$	$4.8 \cdot 10^{-3}$	2.56	64

15 It can be observed that the distribution of Fig. 9a is unsuitable for photon guiding (according to the above-mentioned conditions), while the distributions of Figs. 9b-9d have values of  $\sigma$  and  $N$  suitable for photon guiding.

Figs. 10a-10d show the group velocity distributions for  $R=0.27$  and  $n$  varying as above (2, 2.5, 3.25 and 3.5). As previously, the value of  $\omega_n$  providing the best distribution has been chosen in each graph.

20 Table II reports, for the different curves of Figs. 10a-10d, the values of the characteristics parameters.

TABLE II ( $R=0.27$ )

	$n$	$\omega_n$	$\sigma^2[\text{rad}^2]$	$K[\text{rad}^4]$	$\Delta h$	$N[\%]$
<b>Fig. 10a</b>	2	0.3059	$1.6973 \cdot 10^{-2}$	$4.46 \cdot 10^{-3}$	3.18	64
<b>Fig. 10b</b>	2.5	0.2479	$1.3388 \cdot 10^{-2}$	$4.73 \cdot 10^{-3}$	5.64	70
<b>Fig. 10c</b>	3.25	0.1931	$1.1684 \cdot 10^{-2}$	$5.57 \cdot 10^{-3}$	7.01	70
<b>Fig. 10d</b>	3.5	0.1798	$1.2108 \cdot 10^{-2}$	$5.47 \cdot 10^{-3}$	5.19	71

It can be observed that all the four distributions suitable for photon guiding, that the distributions of **Fig. 10b** is a preferable condition, and the 5 distributions of **Fig. 10c** and **Fig. 10d** are more preferable conditions for photon guiding.

Table III reports the complete results of the simulation, wherein  $R$  is varied between 0.15 and 0.45.

In particular, Table III shows, for each possible combination of values of 10 the parameters  $R$ ,  $n$ , the value of the  $\omega_n$  that allows maximizing the guiding effect.

TABLE III

$R$	$n = 1.5$	$n = 2$	$n = 2.5$	$n = 3.25$	$n = 3.5$
0.15	0.3862	0.2908	0.233	0.1796	0.1669
0.18	0.3879	0.2925	0.2348	0.1813	0.1685
0.21	0.3905	0.2955	0.238	0.184	0.1711
0.24	0.3943	0.2999	0.2421	0.1879	0.1748
0.27	0.3996	0.306	0.248	0.1932	0.1799
0.3	0.4066	0.3142	0.256	0.2005	0.187
0.33	0.416	0.3254	0.2671	0.2107	0.1968
0.36	0.4283	0.3405	0.2823	0.2246	0.2103
0.39	0.4441	0.3605	0.3028	0.2439	0.229
0.42	0.4638	0.3875	0.3321	0.2741	0.259
0.45	0.4902	0.4299	0.3859	0.3409	0.3295

In Table III, three areas have been delimited by different lines, to identify preferred conditions of photon guiding, by taking into account not only the values of  $\sigma$  and  $N$  but also the other parameters that characterize the group velocity distribution. In particular, the thin line identify possible conditions of photon guiding, double thin line identify more preferred conditions of photon guiding and heavy line identify still more preferred conditions of photon guiding.

Table IV indicates, for each couple of values ( $R, n$ ) the percentage of points of the group velocity distribution within an angular range of  $\pi/9$  about the considered propagation direction, in relation with the optimum values of  $\omega_n$  detected for each couple, i.e. in relation to the values of Table III. The analysis has been restricted to the ranges of values of more interest. Areas corresponding to the preferred conditions of photon guiding have been delimited by different kind of lines, as in Table III.

15

TABLE IV

R	n=2	n=2.5	n=3.25	n=3.5
0.21	38%	53%	62%	64%
0.24	51%	66%	73%	69%
0.27	64%	70%	70%	71%
0.3	64%	69%	72%	70%
0.33	68%	71%	70%	72%
0.36	68%	70%	72%	72%
0.39	65%	70%	72%	73%
0.42	65%	69%	74%	71%
0.45	50%	86%	72%	71%

Table V shows the value of variance  $\sigma^2$  corresponding to the sets of values of Table III. The analysis has been restricted to the ranges of values of more interest. Areas corresponding to different conditions of photon guiding have been delimited by different kind of lines, as in Table III.

TABLE V

R	n = 2	n = 2.5	n = 3.25	n = 3.5
0.21	0.025	0.020	0.018	0.018
0.24	0.018	0.013	0.012	0.014
0.27	0.017	0.013	0.012	0.012
0.3	0.015	0.013	0.011	0.016
0.33	0.013	0.012	0.011	0.011
0.36	0.014	0.012	0.011	0.010
0.39	0.015	0.011	0.011	0.011
0.42	0.014	0.013	0.010	0.009
0.45	0.019	0.013	0.010	0.012

This example shows that it is possible to determine terns of values of  $R$ ,  $n$  and  $\omega_n$  that identify conditions of photon guiding.

5

### Example 2

The same simulation has been performed for a photonic crystal having a square array of holes. Differently from above, the percentage of points 10 originally in a range of  $\pi/2$  about the considered propagation direction that have been concentrated within an angular range of  $\pi/6$  is now considerd. The parameters  $R$  and  $n$  have been varied between 0.15 and 0.45 and between 2 and 3.5, respectively. Table VI reports the results of this simulation. In particular, Table VI shows, for each possible combination of values of the 15 parameters  $R$ ,  $n$ , the value of  $\omega_n$  that allows maximizing the guiding effect.

TABLE VI

R	n = 2	n = 2.5	n = 3.25	n = 3.5
0.15		0.2043	0.1554	0.1444
0.18		0.2029	0.1563	0.1455
0.21		0.2045	0.1579	0.1469
0.24		0.2077	0.1602	0.1492
0.27		0.2104	0.1636	0.1522
0.3	0.2655	0.2154	0.168	0.1568
0.33	0.2724	0.2223	0.1745	0.163
0.36	0.2819	0.2323	0.1836	0.1719
0.39	0.2944	0.25	0.1955	0.183
0.42	0.3109	0.263	0.2149	0.2028
0.45	0.3374	0.2972	0.2582	0.2487

As above, areas corresponding to a possible condition and a more preferred condition for photon guiding have been delimited by a heavy line and a thin line, respectively.

### Example 3

X-crossing without cross-talk in a photonic crystal according to the present invention has been demonstrated by a numeric simulation.

The simulation has been performed by considering a triangular array of holes filled with air, with a period  $a$  of 0.372  $\mu\text{m}$ . The bulk refractive index  $n$  is 3.5, the normalized spacing  $R$  is 0.42 and the normalized frequency  $\omega_n$  is 0.24. Two beams of light A, B at wavelengths 1550 nm, having a width of about 5  $\mu\text{m}$  are propagated at 60° from each other along two crystal axes. Only the mode TM is considered. Propagation is simulated in a plane x-y, with input of light at  $y=0$   $\mu\text{m}$ . Fig. 11 shows the propagation of the two beams A, B within the photonic crystal. It can be appreciated that the beams cross with no cross-talk.

**Example 4**

A numeric simulation has been performed for demonstrating the flexibility of the photon guiding technique of the present invention, in particular  
5 the possibility of guiding light beams of different dimensions in different positions of the crystal. The same conditions of Example 3 are considered. Three beams of light A, B, C of different width and at a wavelength of 1550 nm are propagated along a same direction of the crystal. **Fig. 12** shows the collimated propagation of the three beams A, B, C.

10

**Example 5**

A further numeric simulation has been performed for determining the behavior of a light beam at the interface between a photonic crystal according  
15 to the present invention and an integrated waveguide of a known type. **Fig. 13** shows, in a plane x-y, a photonic crystal 800 according to the present invention and a conventional integrated waveguide 801. The interface is represented by a line 802 at coordinate y=0.

The photonic crystal 800 has a triangular array of holes filled of air and  
20 a bulk refractive index  $n$  of 3.5. The normalized spacing  $R$  is 0.33 and the operative wavelength is 1550 nm. The normalized frequency  $\omega_n$  is 0.188.

Waveguide 801 is a monomode waveguide, having a width of 4.5  $\mu\text{m}$ , a core refractive index of 3.5 and a refractive index step of 0.01. This waveguide simulates, for example, a ridge waveguide. The bulk material is the  
25 same as that of the photonic crystal.

A normalized intensity of the input beam is detected at a detection point DP distant 5  $\mu\text{m}$  from the interface 802. It has been observed that the beam intensity at DP is about 98.76% of the input beam intensity. It has also been observed that losses at the interface 802 are small.

30